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An experimental test-bed has been constructed for evaluating synchronization, equalization, and interference cancellation algorithms for digital communications. The transmitter portion of the test-bed consists of a baseband digital modulator composed of either a DSP development station or a custom digital circuit, a digital up-converter, and an RF transmitter unit. This configuration provides sophisticated digital modulations for wireless communications in an easily adaptable framework. The receiver portion consists of an RF receiver unit, an analog-to-digital converter (ADC), a digital down-converter, and a data acquisition unit. The RF receiver, essentially the reverse function of the RF transmitter unit discussed above, receives the RF signal and converts it to an IF for further processing. This provides a wide frequency coverage, a large dynamic range, a built in automatic gain control (AGC), and a baseband downconverter. The local oscillator (LO) is generated by a synthesized signal generator. The overall configuration provides a high performance flexible system for digitizing and outputting sampled data for further processing. The baseband data is stored in a PC using the data acquisition system and transferred to a workstation running SPW for analysis and demodulation. This test-bed serves as a general purpose RF transmitter and receiver allowing concentration of efforts on baseband algorithms and thereby rapid prototyping for broadband applications as in GPS or wideband CDMA.

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DURIP FY 1999: Research Instrumentation for a Wireless Communications Research Laboratory

Final Report

Air Force Office of Scientific Research

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1 DESCRIPTION OF EQUIPMENT PURCHASED

A summary of the equipment purchased with DURIP grant number F49620-98-1-0225 is given in Table 1. A breakdown of costs for each of the major items listed in Table 1 is delineated in Tables 2, 3, 4, and 5. AFOSR/NM provided $78K of the $104K equipment purchase; Purdue provided the remaining $26K in the form of matching funds.

The two major pieces of RF hardware equipment purchased are the same as those requested in the original proposal, namely the HP Vector Signal Analyzer and the HP Signal Generator. However, the prices and options available on these items changed in the one year's time frame between when we submitted the proposal on 20 August 1997 and when the matching funds from Purdue were disbursed on 19 August 1998. As indicated in Table 1, the final price for the HP Vector Signal Analyzer was significantly lower than the budgeted price by about $14K. This reduction in price was achieved through negotiations with HP whereby we were able to achieve the same functionality as an HP89441A by (i) combining the HP89410A and HP89431A products and (ii) choosing additional options. The breakdown of costs for the HP Vector Signal Analyzer is delineated in Table 2.

The reduction in price of the HP Vector Signal Analyzer allowed us to do a number of things to enhance the capabilities of the experimental set-up facilitated by this grant. First, it allowed us to purchase several more options for the HP Signal Generator. In particular, it allowed us to buy two options related to CDMA multi-user wireless communications. This was vitally important given the evolution of both military and commercial wireless communications systems towards direct-sequence spread spectrum radios. Ultimately, the price for the HP Signal Generator was approximately $6.5K higher than the budgeted price. The breakdown of costs for the HP Signal Generator is delineated in Table 3.

Second, Purdue Engineering Computer Network personnel negotiated a promotion deal with Sun Microsystems allowing us to purchase not only more computers than the number originally budgeted, but also computers with substantially more processing power than that described in the original proposal. Whereas the original proposal requested two Ultra 1 Workstations, this promotion combined with the price reduction of the HP Vector Signal Analyzer allowed the purchase of four Ultra 10 Workstations. The breakdown of costs for these four Ultra 10 Workstations is delineated in Table 4.

Finally, the price reduction of the HP Vector Signal Analyzer also allowed us to purchase two software packages related to RF multipath propagation channel modelling. These two software packages, SMRCIM and SIRCIM, are produced by Wireless Valley Communications, Inc., and came on the market after the submission of the original proposal. These software packages allow testing of candidate algorithms for synchronization, equalization, and interference cancellation under real-world multipath conditions synergistically with attendant experimental RF testing.

Since the software packages SMRCIM and SIRCIM do not run on the Sun Workstation platform, this necessitated the purchase of a PC as indicated in Table 1. Again, this purchase was facilitated by the price reduction negotiated for the HP Vector Signal Analyzer as well as through matching funds provided by Purdue. This PC also can be used to download, store, and process experimental data as depicted in the receiver portion of the experimental test-bed in Figure 1.

List of Tables

Summary of Total Costs			
Equipment	**Subtotal**	**Budget**	**Comments**
HP Vector Signal Analyzer	$52,880	$67K	See Table 2 for breakdown of costs.
HP Signal Generator	$28,760	$22K	See Table 3 for breakdown of costs.
Sun Ultra 10 Workstations	$17,288	$15K	See Table 4 for breakdown of costs.
SMRCIM/SIRCIM Software	$2,490	$0	See Table 5 for breakdown of costs.
PowerComputing PowerCenter PRO210	$2,582	$0	Dedicated platform for running SMRCIM/ SIRCIM.
Total Cost:	$104,000	$104K	includes 25% Purdue matching funds.

Table 1: Summary of Costs for Equipment Purchased.

Purchased Equipment: Hewlett-Packard Vector Signal Analyzer		
Part No.	**Cost**	**Description**
HP89441A	$35,556	Combination of HP89410A and HP89431A. DSP based single channel signal analyzer with internal disk, color display, AM/FM/PM demodulation, and internal source.
Option 1C2	$312	Adds 160 commands that are syntax compatible with HP BASIC on HP9000 computers
Option AY5	$437	Adds ovenized frequency reference oscillator to improve frequency stability.
Option AY7	$2,808	Adds a full second 10 MHz input channel. Two input channels allow one to measure cross-correlation and coherence.
Option AY9	$936	Extends time capture memory from 64 KSamples to 1MSample.
Option AYA	$2,808	Adds vector modulation analysis for characterizing digital modulation schemes and other simultaneous amplitude and phase modulations.
Option AYB	$1,872	Adds Waterfall and Spectrogram capabilities including flexible 3-D displays for monitoring signal trends over time.
Option UG7	$936	Provides for remote displays using X11 Windows protocol and file transfer capability via FTP.
Option UTH	$1,488	Adds 20 MB RAM to standard 1.5 MB RAM and a 2nd HPIB interface for basic file transfer & programming.
Option AYH	$2,295	Adds analysis of 16, 32, 64, and 256 QAM, 8 VSB, and 16 VSB digital video signal formats.
Option AY8	$3,432	Adds an Internal RF Source capable of generating CW, random noise, periodic chirp, and arbitrary waveforms.
Subtotal:	$52,880	includes 20 % educational discount

Table 2: Breakdown of Costs for HP Vector Signal Analyzer.

Purchased Equipment: Hewlett-Packard Digital Signal Generator		
Part No.	**Cost**	**Description**
ESG-D E4432B	$14,080	RF signal generator: 250 KHz- 3 GHz with 13 to -136 dBm power. Analog I/Q inputs. Internal 50 KHz waveform generator. Wideband AM & FM, PM, and pulse modulation. Frequency & power sweep.
Option UND	$4,800	Adds internal dual arbitrary waveform generator. Low noise 14-bit DAC's. 1 MSample/channel waveform sequencer.
Option UN8	$4,080	Adds real-time I/Q baseband generator with TDMA standards. Suuports NADC, GSM, TETRA, PHS, PDC, DECT, and custom modulation.
Option UN9	$1,200	Add 7 Mbits RAM for data patterns to the real-time I/Q baseband generator.
Option UN5	$1,600	Multi-channel CDMA personality. Provides IS-95 CDMA with pre-configured waveforms including pilot, 9 channel, or 64 channels and single reverse. Flexible channel editor, data rates, and filtering.
Option H97	$3,000	Multi-channel Wideband-CDMA personality.
Subtotal:	$28,760	includes 20 % educational discount

Table 3: Breakdown of Costs for HP Signal Generator.

Purchased Equipment: Sun Ultra 10 Workstations				
Part No.	**Unit Cost**	**Qty**	**Subtotal**	**Description**
22-UEA1A9L-64AGIP	$3,395	4	$13,580	Ultra 10 System UNIX 300 MHz, 512-KB cache, 4.3-GB hard disk drive, 64-MB DRAM, 10/100BASE-T Ethernet, Creator3D Series 3, double-buffered
X7119AIP	$700	4	$2,800	19-inch Color Monitor.
X3872A	$45	4	$180	Video Adapter.
IQDIMM4X72-60EDO3.3B	$182	4	$728	add'l 64-MB DRAM.
Subtotal:			$17,288	includes 40 % educational discount

Table 4: Breakdown of Costs for Sun Ultra 10 Workstation Systems.

Purchased Software: Wireless Valley Communications		
Title	**Cost**	**Description**
SMRCIM	$995	Urban/Microcell Channel Modelling Tool. Statistical channel modelling tool for urban microcell and macrocell mobile radio channels. Wideband impulse responses and narrowband fading signals are generated over a frequency range of 400 MHz to 60 GHz.
Maintenance Option	$250	Annual Maintenance and Support Agreement for SMRCIM.
SIRCIM	$995	Indoor RF Channel Modelling Tool. Wideband statistical channel modelling tool for in-building environments from 400 MHz to 60 GHz. Provides narrowband fading and multipath impulse response models for a wide range of in-building environments including factories, office buildings, stores, and hospitals. Includes impulsive noise models for the UHF, VHF, and NII bands.
Maintenance Option	$250	Annual Maintenance and Support Agreement for SIRCIM.
Subtotal:	$2,490	no educational discount

Table 5: Breakdown of Costs for Multipath Channel Modelling Software Tools.

2 SUMMARY OF ONGOING/PLANNED RESEARCH PROJECTS USING DURIP EQUIPMENT

2.1 Experimental Test-Bed

Fig. 1 shows the equipment configuration constructed with the support of this DURIP grant. The transmitter portion of the equipment consists of a baseband digital modulator consisting of either a DSP development station or a custom digital circuit, a digital up-converter, and an RF transmitter unit. This hardware is implemented in a combination of a DSP evaluation board, an Analog Devices AD7008 Digital Up-Converter, and discrete mixers, filters, and amplifiers for the RF transmitter. This configuration can provide sophisticated digital modulations for wireless communications in an easily adaptable framework.

The receiver portion consists of an RF receiver unit, an analog-to-digital converter (ADC), a digital down-converter, and a data acquisition unit. The RF receiver, essentially the reverse function of the RF transmitter unit discussed above, receives the RF signal and converts it to an IF for further processing. An Analog Devices AD607 evaluation module is employed for this function. It provides a wide frequency coverage, a large dynamic range, a built in automatic gain control (AGC), and a baseband downconverter. The LO is generated by a synthesized signal generator. The digital down-converter is implemented with a Harris HSP50016 evaluation module. The current configuration provides a high performance flexible system for digitizing and outputting sampled data for further processing. The baseband data is stored in a PC using the data acquisition system and transferred to a workstation running SPW for analysis and demodulation.

The equipment purchased serves as a general purpose RF transmitter and receiver allowing much more rapid prototyping for broadband applications as in GPS or wideband CDMA. Its use allows us to concentrate our efforts on baseband algorithms which are more amenable to university endeavors than is the rather specialized topic of RF design.

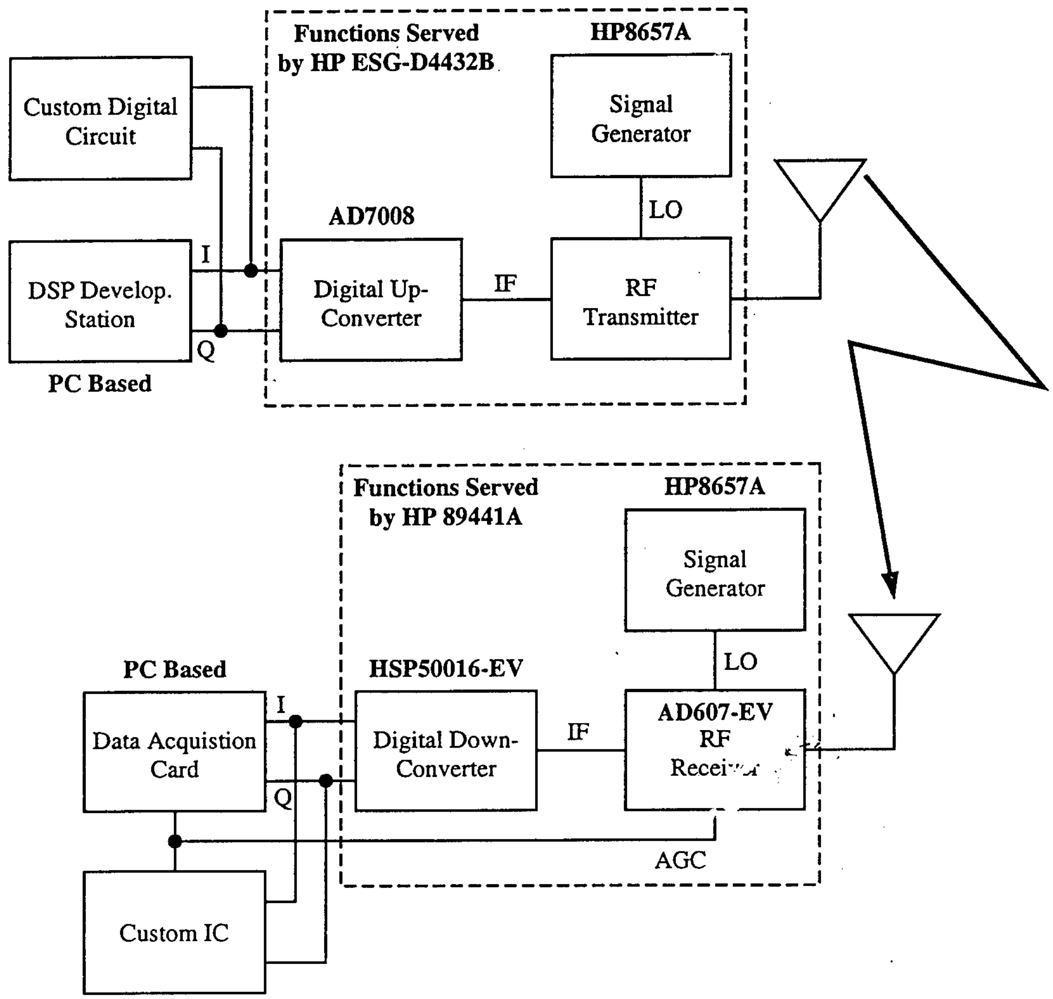

Figure 1: Experimental Test-Bed.

2.2 New World Vista Topic 20. Jam-Proof Area Deniable Propagation: Anti-Jam Protection for GPS Via Robust, Computationally Efficient Space-Time Adaptive Processing

The purchase of the digital RF signal generator and the vector signal analyzer greatly supports the objective of the "parent" AFOSR grant to identify, develop, evaluate, and demonstrate innovative space-time adaptive processing schemes that protect GPS user equipment against intentional and unintentional interference. The anti-jam space-time filter needs to be capable of suppressing different interferer types, with particular emphasis on multiple broadband Gaussian noise interferers as dictated by the GPS Joint Programs Office. In addition to providing interference suppression, the filter should allow reception of GPS satellite signals in a stressed environment by maximizing the signal power to interference plus noise power (SINR) for acquisition and tracking of the GPS signal by standard military P(Y) code user equipment. The filter should be targeted for operation within the environment and dynamics characteristics of a high performance fighter aircraft. The goal is to demonstrate higher, yet affordable anti-jam capabilities for GPS user equipment on aircraft and other airborne weapons systems beyond the year 2000.

The GPS anti-jam algorithms developed with support of the parent AFOSR grant are being tested with experimental data generated from the experimental test-bed. The digital RF signal generator purchased allows us to synthesize a number of different types of interference.

Option AY7 purchased for the HP Vector Signal Analyzer allows a second input channel. Figure 2(a) shows an experimental dual antenna receiver. The two-channel data provided by this experimental dual antenna receiver may be analyzed by the HP Vector Signal Analyzer. The use of two antennas allows for the spatial nulling of a single broadband interferer thereby providing proof-of-concept demonstrations for candidate anti-jam spatial filters. The dual antenna receiver, the vector signal analyzer, and the digital RF signal generator provide a flexible testbed for experimentally verifying the candidate anti-jam signal processing schemes.

2.2.1 Protection Performance Versus Hardware/Computational Complexity

Our New World Vista effort is part of a system-level study of the trade-offs between protection performance versus hardware and computational complexity for various integrated levels of processing. Two primary approaches are being investigated: (1) power minimization based space-time preprocessing and (2) SINR maximization based post-correlation space-time processing.

In the power minimization based space-time preprocessor, each sample value fed to the GPS receiver is formed from a linear combination of samples across both space and time. The space-time weights are effected through a tapped delay line behind each digitized baseband antenna output. The goal of the preprocessor is to suppress jammers as best as possible while passing as many GPS signals as possible unaltered. Although the anti-jam space-time filter effected is not optimized for any one GPS satellite signal in terms of maximizing SINR, the advantage of this approach is that the anti-jam space-time filter is a separate component so that a standard digital GPS receiver may be employed.

Three primary space-time preprocessors are being investigated: (1) full dimension joint space-time preprocessor, (2) decoupled space-time preprocessor, and (3) reduced dimension joint space-time preprocessor based on a decoupled cross-spectral metric. Through theoretical performance analysis, extensive Monte Carlo simulations, and testing on "real" GPS data from an experimental antenna array, the performance of these three space-time adaptive preprocessing structures will be investigated in terms of the trade-offs amongst output SINR, convergence rate, cost-effective hardware implementation, and computational complexity.

Full dimension and reduced dimension joint space-time post-correlation processing based on SINR maximization will also be investigated. In order to avert processing at the chip rate, the performance of an additional post-correlation algorithm will be investigated through experimental implementation based on a blind adaptive beamforming algorithm developed previously by the PI for narrowband

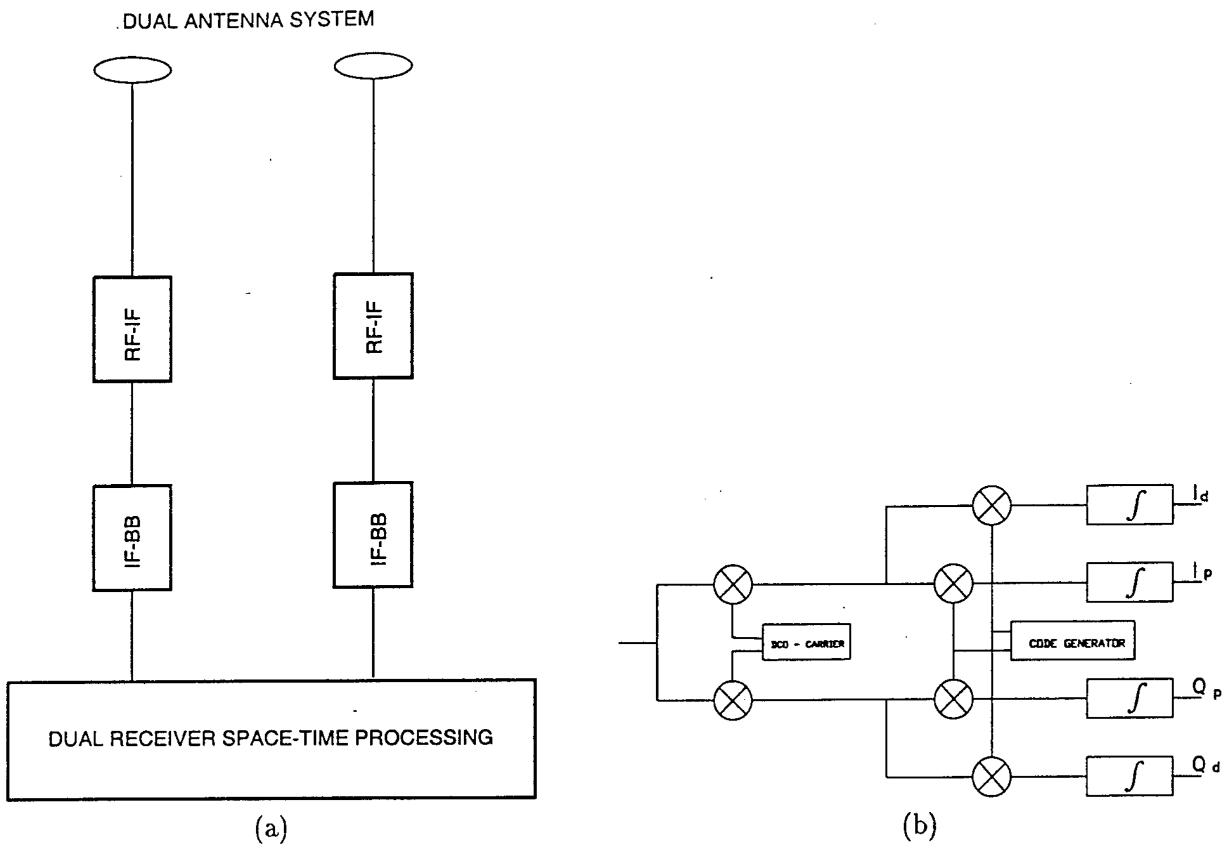

Figure 2: (a) Block diagram of dual antenna receiver. (b) Structure of IF-BB Stage.

digital communications. This approach allows the use of a general purpose microprocessor employing a sampling rate equal to just several times the bit rate.

2.2.2 Receiver Architecture

A block diagram of the prototype dual antenna array receiver is shown in Figure 2(a). Each antenna element is a low cost *stacked patch antenna.* This configuration provides a wider bandwidth that allows the reception of two services simultaneously: GPS and INMARSAT. To achieve circular polarization, a 90° hybrid is placed below each element antenna. Following that are two Low Noise Amplifiers (LNA) in MMIC (Microwave Monolithic Integrated Circuit) technology.

After the dual antenna receiver described above, the Radio Frequency signals (RF) are handed to two standard DS-SS receivers with the special feature that all of them are locked to the same Local Oscillator (LO). These two spread spectrum receivers are basically composed of two stages: the downconversion from Radio Frequency to Intermediate Frequency (IF), and the Intermediate Frequency processing to get the Base Band (BB) signals. The design and implementation of each of these two stages are described below, paying special attention to the Digital Signal Processing involved in the IF-BB stages.

Two ASIC's (Application Specific Integrated Circuits) are used in the implementation of the hardware. The first one accomplishes the down conversion from RF to get an Intermediate Frequency signal centered at 4.32 MHz. The output of the last mixer is sampled at 5.71 MHz and coded with only 2 bits. The second ASIC, a Digital Signal Processor (DSP), accomplishes the following tasks: down conversion to Base Band accounting for the Doppler offset, the correlation with the code corresponding to each satellite, bit synchronization, and the symbol decision relative to the BPSK constellation.

All the Digital Signal Processing involved in the IF-BB conversion is guided by a low cost microprocessor. The microprocessor serves the second integrated circuit asynchronously, i.e., on demand. The same microprocessor carries out the rest of the tasks needed in a GPS receiver which exceed that strictly necessary in a standard DS-SS receiver. They include the estimation of the satellite-user distance, acquisition of the Universal Coordinated Time (UCT), decoding of the navigation message sent by the satellites and the computation of the users location. In addition to the aforementioned tasks, the microprocessor has to control the Digital ASIC and perform the beamforming as explained in the next section. This receiver architecture provides a large degree of flexibility and robustness.

The digitalized signal is provided to the IF-BB stage at a sampling rate of 5.71 MHz. Figure 2(b) outlines the structure of the parallel processing carried out on these signals. The processing gain in a DS-SS system is proportional to the ratio of the RF bandwidth to the bandwidth after the decorrelation with the desired GPS satellite code. The RF bandwidth is fixed by the chip rate. It has to be at least twice the chip rate. The minimum bandwidth the system should have after the decorrelation is the bit rate (in base band or twice it at IF). Thus, a narrowband filter has to be placed after decorrelation to achieve a high processing gain that permits a good suppression of jammers and receiver noise, ideally a bandwidth equal to the baud rate (50 Hz for GPS). Such a narrow band means that any signal that differs in frequency more than 50 Hz from the expected one is filtered out of the receiver output.

On the other hand, the received frequency might be Doppler shifted up to ± 5KHz away from the nominal L1 (or L2) frequency due to GPS satellite motion. Therefore, the receiver has to have a very wide bandwidth relative to the bit rate. Similar comments hold relative to the code: in order to achieve high resolution in the location estimate provided by GPS, a very accurate estimation of the code delay is required. However, codes with a delay larger than (or equal to) half a chip are suppressed by the correlator. To balance these opposing requirements, the carrier and code recovery are done simultaneously in two stages: search and tracking.

The search stage consists of successive trials with different frequencies for the carrier and different delays for the code. After the search process, the worst case is a local oscillator 500Hz away from the actual received carrier and a generated code delayed less than half a chip with respect to the received code. Then the tracking stages begin for both carrier and code. Since the modulation for GPS is BPSK, the tracking of the carrier cannot be done with a regular PLL but with a Costas Loop. The tracking of the code delay is performed by a DLL (Delay Lock Loop). The Costas Loop estimates the phase error as the result of an iterative search. The phase error is measured by a phase detector which can be implemented in different ways in the digital receiver. Although the more reasonable phase detector would be to compute $\text{atan}\left(\frac{Q_p}{I_p}\right)$, the prototype uses the lower cost approximation $sign(Q_p)I_p$. The design of the DLL follows a parallel optimization similar to the Costas Loop. In this case, the input to the loop is $I_p^2 + Q_p^2 - I_d^2 - Q_d^2$.

Both the tracking of the carrier and the code are governed by only one of the two receivers (Master) and the phase of the carrier and delay of the code are updated identically in the other five receivers (Slaves). At this point, the process in charge of the beamforming is fed with the $I_p + jQ_p$ complex envelope at a rate of one sample per millisecond. This complex envelope is available for each of the two antennas.

2.2.3 Low-Complexity Post-Correlation Blind Adaptive Beamforming

A novel algorithm for narrowband systems that adapts the digital beamformer to the interference scenario via maximization of the output SINR has been developed by the PI. The proposal for the parent AFOSR grant details how this algorithm may be adapted for post-correlation beamforming for GPS signal reception. This approach allows the use of a general purpose microprocessor employing a sampling rate equal to just several times the bit rate.

An experiment was conducted in which the experimental GPS receiver was programmed to receive a GPS signal arriving at an elevation angle of 30 degrees with respect to the boresite axis of the

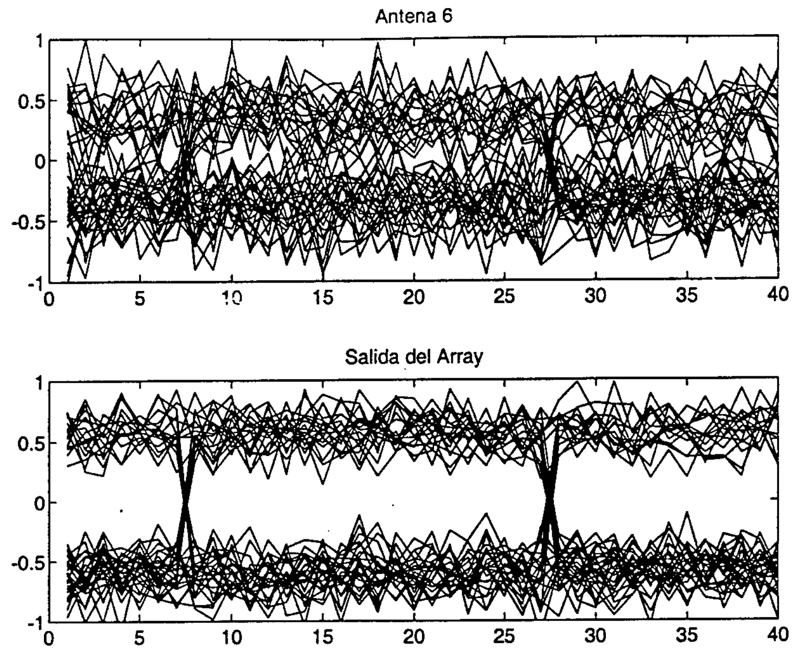

Figure 3: Eye diagram at one of the antennae and at the output of the array processing.

array. After despreading, the SNR of the GPS signal was roughly 10 dB per element. In addition, interference was intentionally injected by a nearby radiating antenna at an angle of 20 degrees with respect to boresite, and at a power level 40 dB above the desired GPS signal (prior to despreading.) Figure 3(b) shows the complex demodulation of the signal at each element and the output obtained with adaptive beamforming using the space-only post-correlation blind scheme. In order to give some idea of the improvement achieved, the eye diagram at the antenna element with the best signal to noise ratio is compared with that obtained at the beamformer output. It is clear that the jammer has been sufficiently rejected so as to "open up the eye." As a proof of concept, this experiment reveals the scheme to be promising. However, further testing on real experimental data will be done. In addition, real time implementation studies will also be conducted.

2.3 Globally Optimal Adaptive Algorithms and Stochastic Approximations

Adaptive algorithms and stochastic approximations are a statistical version of the common recursive procedures of numerical analysis (i.e., root finding and optimization algorithms). They are routinely applied to solve real-world complex problems with imprecise information for which purely analytical procedures cannot be used. They have found widespread application to a wide variety of optimization, regulation and tracking problems in the fields of system identification, adaptive filtering, adaptive control, and several aspects of pattern recognition. However, when used to solve nonconvex optimization problems the standard adaptive algorithm performance is often unpredictable and/or undesirable, sometimes converging to a strictly local extremum. The successful completion of this work will provide a class of adaptive algorithms with a desirable global behavior which possess a simple implementation and a rigorous theory. No such theory exists under the realistic conditions that the algorithms are typically applied. This work will also provide a decisive numerical study of competing adaptive algorithms for solving global learning and tracking problems which are routinely encountered by the military.

Global optimization of stochastic systems has a great many applications in applied probability and

statistics, including important problems in operations research, the physical sciences and engineering. The general problem involves a partially observed stochastic system whose parameters are tuned to optimize some (nonconvex) measure of performance. The problem areas that interest us most are in engineering, and we mention some important examples below which we have specific background and/or interest in. Other applications can be found in the large and developing literature, which is motivated by both the difficulty and importance of globally optimal solutions.

1. **Communications and Signal Processing.** This is a classical area where many algorithms were first developed and applied. Some problems of current interest include (i) blind equalization (to reduce interference without training data in broadcast or covert transmission); and (ii) time delay estimation (to perform high data rate multipath channel estimation and tracking). The solution of these problems is important for reliable, efficient and secure high data rate communications. The global aspect of the optimization arises from non-prediction based error criteria and/or nonlinear parameterization.

2. **Communications and Computer Networking.** This is an emerging area which includes problems such as (i) channel allocation (to develop sharing schemes which take into account the user requirements); and (ii) scheduling and coordination (to coordinate communications at multiple levels within and between cells). The solution of these problems is critical for high bandwidth multimedia networks (speech, image, video, data). The global aspect of the optimization arises from using localized strategies which nontheless seek to optimize global network performance.

3. **Low Power Electronics Design for Complex Systems.** The goal is to minimize energy consumption in design of a complex electronics system subject to constraints on performance, security, size etc.. These applications involve optimizing circuits for low switching activity (energy dissipation in CMOS circuits is mainly associated with switching current which charges and discharges capacitance at different nodes of a circuit). Global (and hierarchical) aspect of the optimization arises from combined system/implementation-based cost function and constraints.

2.3.1 Planned Experimentation

The experimental test-bed will be used to perform relevant experimental work on the physical layer communications problems specified above. The modem we have constructed and tested has all the key algorithms implemented in software, currently either real-time DSP code (Motorola 5600 family) or high level software (Signal Processing Workstation (SPW)). The extensive use of SPW is significant in that it permits rapid constructions of simulations for digital communications systems. Newly created modules can be saved and used in future simulation work, and also transferred to sponsors for further studies and collaboration. The experimental test-bed will be used to run realistic experiments on equalization and demodulation algorithms (including the use of interference rejection and diversity techniques) whose development is predicated on idealized fading channel models. These flat and frequency selective fading channel models are an approximation and we intend to test how theory and practice match. Finally we have implemented fairly sophisticated coded modulation schemes which can achieve up to 4 bits/baud data rate while achieving a minimum Hamming distance of 3. Codes like these typically have a large number of states and require a complex demodulation algorithm. The four SUN Ultra-10 workstations are being used to conduct substantial MATLAB and SPW-based simulations for this and other realistic wireless scenarios.

2.4 High Performance Narrowband Wireless Communications

Commercial applications of narrowband channels are abundant. They include paging services, general voice and data communications, delivery vehicle tracking and management, and sensor telemetry

transmission in applications including intelligent transportation systems (ITS), medical monitoring, and the military. Given these kinds of challenging applications and the growing demand for RF spectrum, future commercial narrowband wireless communications equipment will need both high spectral efficiency in data transmission capacity and the capability to support multiple operating modes (mobile, point–to–point, and multiple access).

Research applicable to narrowband radio services (NRS) is ongoing in the Communications Research Laboratory at Purdue. This work has resulted in an experimental modem testbed and extensive field testing. These modems include such advanced features as: (1) spectrally efficient pulse shaping, (2) large QAM constellations (up to 128QAM), (3) linear equalization, (4) pilot symbol assisted modulation, (5) interleaved coded modulation, (6) frequency offset transmitter diversity, (7) synchronization optimized for time-varying fading, and (8) soft decision coding optimized for time-varying fading. An experimental license to transmit in the NRS band has been granted by the Federal Highway Administration (FHWA) for the Purdue work in support of the FHWA Intelligent Transportation System (ITS) program. This research has worked to maintain high performance while increasing the spectral efficiency of narrowband wireless communications. This grant has provided the facilities to continue and expand this research.

2.4.1 Narrowband Wireless Challenges

The most important characteristic in shaping a wireless communication system design is multipath propagation. In general, multipath propagation will cause both intersymbol interference (ISI) and time varying fading. In a narrowband system the duration of the modulation symbols are very long in comparison to the multipath delay spread on the channel and hence all the multipath is effectively combined into a single multiplicative distortion process (i.e., frequency nonselective fading). For example, when using the NRS spectral allocations the symbol time is lower bounded by 250 ms while the multipath spread is rarely greater than 2 ms. This environment generates very little ISI, and therefore rarely requires advanced equalization techniques for modulations using smaller constellations. However, as the spectral efficiency of narrowband wireless modems increases the need for equalization will increase as even a small amount of ISI will substantially degrade performance. The experimental work is enabling us to determine how large constellations must become before classical demodulation techniques fail and new algorithms are needed.

The received signal strength on a frequency nonselective wireless channel varies significantly with the positions of the transmit and receive antennas. In a simplistic model the received signal phase for each multipath will be proportional to path length, i.e.,

$$\theta(t) = 2\pi d(t)/\lambda$$

where $\theta(t)$ is the time varying multipath phase, $d(t)$ is the path length and λ is the wavelength of the carrier. Furthermore, as the position of the transmitter or receiver changes, each multipath will have a different path length inducing a different phase on that multipath signal. If a line-of-sight path does not exist and the multipath signal strengths are comparable then slight changes in phase can produce significant changes in the composite signal amplitude. This characteristic produces a location dependent amplitude variation. Fig. 4, an example of the received signal strength at the receiver of a moving vehicle, shows the great variability of the received signal strength as a function of location. Exploiting this variability with location is important in producing high performance bandwidth efficient data communication. Consequently, having an experimental capability to explore this spatial signal variability has been vitally important for continued research in this area.

The frequent occurrence of deep fades in wireless transmission (see Fig. 4) makes it difficult to produce reliable communication with standard modulation and demodulation techniques at a reasonable signal to noise ratio (SNR). The worst case performance in wireless data communications is produced when no line-of-site path exists, a situation often modeled as Rayleigh fading. Fig. 5 shows a plot

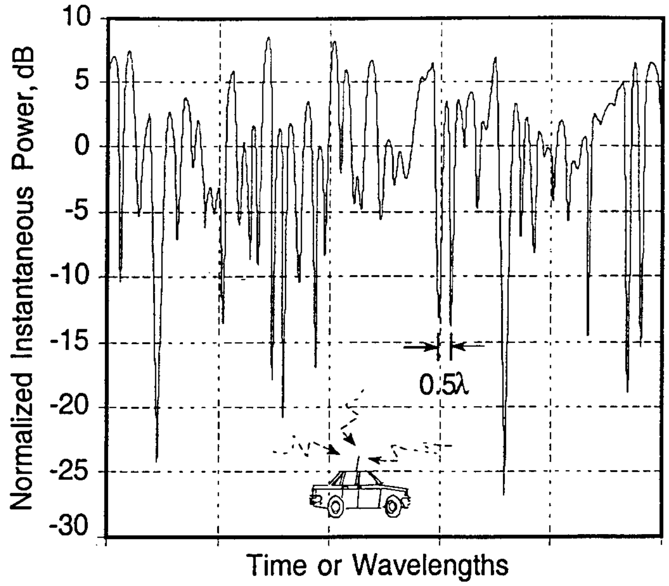

Figure 4: The received signal amplitude versus time for a moving antenna.

comparing the bit error probability (BEP) of ideal coherent demodulation of uncoded 16QAM modulation for a frequency nonselective Rayleigh fading channel and for a nonfading channel (AWGN). Clearly the BEP performance in a fading channel is much worse than in a nonfading channel. In fact, the BEP is dominated by the relatively infrequent times when the received signal is in a deep fade (see Fig. 4). Mitigating the effects of these deep fades using diversity techniques is critical to achieving reliable communication at a reasonable SNR. Diversity is essentially transmitting the information over a separate realization of a fading channel. Fig. 5 shows good performance at practical values of SNR is only achievable with diversity techniques. The experimental test-bed is enabling us to fully explore the performance of the different possible diversity techniques that can be used in narrowband wireless communications.

The challenges of spectrally efficient narrowband wireless data communication on the NRS spectral allocations are:

- Combating location dependent signal fading,
- Combating large frequency uncertainty due to the large differences between the symbol rate and the carrier frequency,
- Achieving a microwave system design that supports large bandwidth efficient constellations,
- Achieving the greatest possible spectral reuse for multiple access operation.

These challenges produce a need for continued experimental work in narrowband wireless communications. The following subsections outline some of the ongoing/planned research along these lines.

Large Constellations

The goal of the research ongoing in narrowband data communications is to greatly increase the spectral efficiency while maintaining acceptable performance. Increased spectral efficiency can only be obtained by the use of larger constellations and more efficient coding schemes. Larger constellations will be more susceptible to ISI generated by multipath propagation in the wireless channel. The main point is that narrowband channels are not completely frequency nonselective and this characteristic is more pronounced as spectral efficiency is pushed higher via large constellations (say 64 QAM or

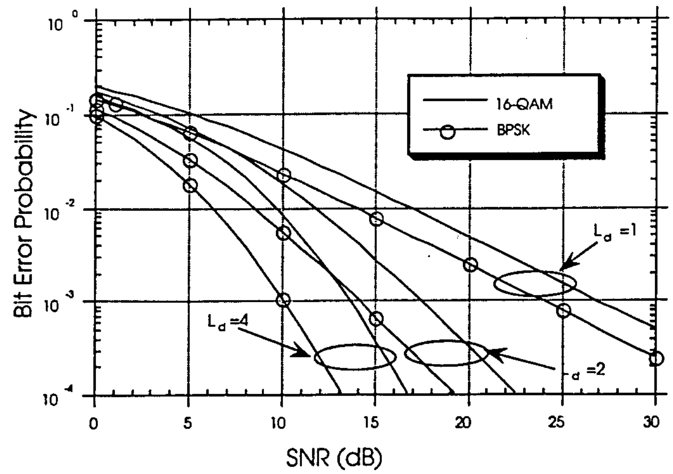

Figure 5: The bit error probability for uncoded BPSK and 16QAM for AWGN channel, a Rayleigh fading channel, and a Rayleigh fading channel with diversity reception (L_d is the diversity level).

128 QAM). Experimental research is being conducted to quantify the effects produced by the wireless multipath channel for demodulation with large constellations.

Transmitter Diversity

On a forward link (i.e., infrastructure to remote terminal), diversity is best achieved at the transmitter. To maintain small size and low cost for remote units, operation with only one antenna and receiver is desirable. Using transmitter diversity enables this type of a design while still achieving high performance. The essential idea in transmitter diversity is to transmit signals (not necessarily of the same modulation) from multiple antennas which are either spatially separated or have a different polarization. The multiple transmitted signals propagate through separate channels and arrive at the receiver with different multiplicative distortions.

Significant research has examined signal design for the transmitter diversity problem and several high performance structures have resulted. The wireless modem built in the Communications Research Laboratory at Purdue University uses a slight frequency offset between each antenna combined with pilot symbol assisted channel estimation and interleaved coded modulation to achieve high performance. Additionally, a more principled signal design methodology for transmitter diversity communications is being developed. We are currently extending this methodology to produce high performance bandwidth efficient signal designs using transmitter diversity. The theory developed for transmitter diversity schemes assumes that the channel gains from the different antennas to the receiver are independent random variables. This can be achieved in any environment if the antennas are spaced far enough apart. The more interesting question involves antenna placement using a limited spatial separation. Experimentation is being conducted to verify the performance of any array geometry or modulation scheme proposed.

Receiver Diversity and Interference Suppression

Multiple antennas at the receiver is another method to achieve the desired level of diversity for high performance data transmission. Various high performance methods for diversity combining in narrowband data communications have been examined at Purdue. These algorithms assumed independent signals at each of the antennas. It remains to improve our understanding of antenna spatial geometries for achieving high performance demodulation with diversity. This study can is being accomplished via experimental testing with real modems and propagation environments.

Additionally, multiple antennas can provide significant spatial selectivity in wireless transmissions. This selectivity can be used to null out co-channel users in a multiple access environment. This

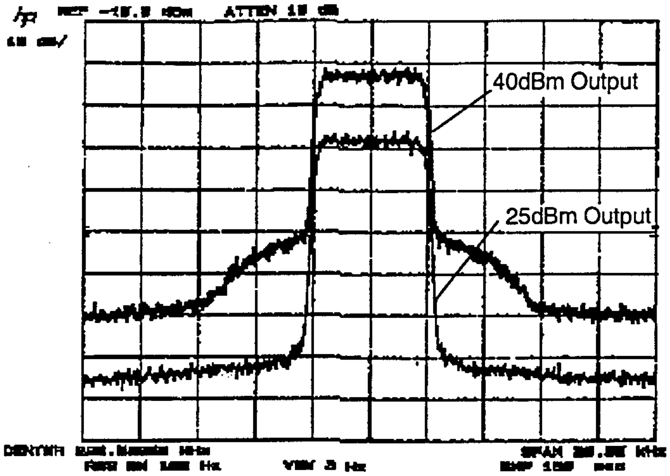

Figure 6: Measured transmitted power spectral density of a 16QAM signal at two output power levels.

multi-user interference in practical data communication systems almost always limits the achievable performance. Designing algorithms to combat this interference is critical to achieving a higher spectral reuse than that achieved in currently deployed systems.

High Power Amplifier Linearization

Wireless systems typically need to produce a relatively high output power at the transmitter. Class-C operation is the most efficient mode of operation for high power amplifiers, but has a nonlinear characteristic. Consequently, until recently modulations for wireless systems have tended to have a near constant signal envelope (e.g., phase modulation). Recent advances in modulation and demodulation techniques for wireless transmissions have seen a switch in emphasis to more nonconstant envelope modulations (e.g., QAM and multi-user CDMA). Using nonconstant envelope modulations in circuits with even moderate nonlinearities can produce adverse effects. For example Fig. 6 shows the output spectrum for two power levels for a bandlimited 16QAM transmission. The lower power transmission meets the FCC spectral emission mask requirement and even though the higher power transmission experiences a relatively benign nonlinearity it does not meet the emission mask specification (the amplifier was a $2000 unit optimized for linearity). This has led to a renewed interest in linear or linearizing amplifier structures. The equipment will be employed to to verify the efficacy of high power amplifier linearization since realistic input signals can easily be generated with the purchased equipment to test potential algorithms.